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**TRACKING POINTS ON
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CURVATURE INFORMATION**

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Février 1992



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Tracking Points on Deformable Objects Using Curvature Information

Suivi de Points sur des Objets Déformables en Utilisant la Courbure*

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Abstract

The objective of this paper is to present a significant improvement to the approach of Duncan et al. [1, 7] to analyze the deformations of curves in sequences of 2-D images. This approach is based on the paradigm that high curvature points usually possess an anatomical meaning, and are therefore good landmarks to guide the matching process, especially in the absence of a reliable physical or deformable geometric model of the observed structures.

As Duncan's team, we therefore propose a method based on the minimization of an energy which tends to preserve the matching of high curvature points, while ensuring a smooth field of displacement vectors everywhere.

The innovation of our work stems from the explicit description of the mapping between the curves to be matched, which ensures that the resulting displacement vectors actually map points belonging to the two curves, which was not the case in Duncan's approach. Moreover, the energy minimization is obtained through the mathematical framework of Finite Elements analysis, which provides a rigorous and efficient numerical solution. Moreover we show that the generalization of our approach can be easily generalized in 3-D to analyze the deformations of surfaces.

We have actually implemented the method in 2-D and we present the results of the tracking of a heart structure in a sequence of ultrasound images.

Résumé

L'objectif de cet article est de présenter une amélioration importante de la méthode présentée par Duncan et al. [1, 7] pour analyser la déformation de courbes dans une séquence d'images 2-D. Cette approche est basée sur le principe que les points de forte courbure ont une signification anatomique et par conséquent sont importants pour la mise en correspondance des points. De plus, cette approche n'est pas sous-jacente à un modèle physique ou géométrique des structures observées dans la séquence d'images.

Nous proposons, comme Duncan et al. [1, 7], une méthode basée sur la minimisation d'une énergie qui préserve la mise en correspondance de points de forte courbure tout en assurant un champ de déplacement régulier.

L'innovation provient de la description explicite de l'application mettant en correspondance les courbes, ce qui garantit que le champ de déplacement met en correspondance des points appartenant aux deux courbes, contrairement à la méthode de Duncan. De plus, la minimisation de l'énergie est faite à l'aide d'une méthode variationnelle et d'éléments finis. La méthode présentée peut être également généralisée au suivi de déformations de surfaces dans des images 3-D.

Nous avons implémenté la méthode dans le cas de courbes 2-D, et nous présentons les résultats obtenus sur le suivi de la valve mitrale dans une séquence échocardiographique.

1 Introduction

Non-rigid motion of deformable shapes is becoming an increasingly important topic in computer vision, especially for medical image analysis. Within this topic, we concentrate on the problem of tracking deformable objects through a time sequence of images.

The objective of our work is to improve the approach of Duncan et al. [1, 7] to analyze the deformations of curves in sequences of 2-D images. This approach is based on the paradigm that high curvature points usually possess an anatomical meaning, and are therefore good landmarks to guide the matching process. This is the case for instance when deforming patients skulls (see for instance [6, 8, 16], or when matching patient faces taken at different ages, when matching multipatients faces, or when analyzing images of a beating heart. In these cases, many lines of extremal curvatures (or ridges) are stable features which can be reliably tracked between the images (on a face they will correspond to the nose, chin and eyebrows ridges for instance, on a skull to the orbital, sphenoid, falx, and temporal ridges, on a heart ventricle to the papillary muscle etc. . .).

As Duncan's team, we therefore propose a method based on the minimization of an energy which tends to preserve the matching of high curvature points, while ensuring a smooth field of displacement vectors everywhere.

The innovation of our work stems from the explicit description of the mapping between the curves to be matched, which ensures that the resulting displacement vectors actually map points belonging to the two curves, which was not the case in Duncan's approach. Moreover, the energy minimization is obtained through the mathematical framework of Finite Elements analysis, which provides a rigorous and efficient numerical solution. Moreover we show that the generalization of our approach can be easily generalized in 3-D to analyze the deformations of surfaces.

Our approach is particularly attractive in the absence of a reliable physical or deformable geometric model of the observed structures, which is often the case when studying medical images. When such a model is available, other approaches would involve a parametrization of the observed shapes [13], a modal analysis of the displacement field [11], or a parametrization of a subset of deformations [2, 14]. In fact we believe that our approach can always be used when some sparse geometric features provide reliable landmarks, either as a preprocessing to provide an initial solution to the other approaches, or as a post-processing to provide a final smoothing which preserves the matching of reliable landmarks.

We have actually implemented the method in 2-D and we show how to generalize the approach

in 3-D. We present the results of the tracking of a heart structure in a sequence of 2-D ultrasound images.

2 Modelling the Problem

Let C_P and C_Q be two boundaries of the image sequence, the contour C_Q is obtained by a non rigid (or elastic) deformation of the contour C_P . The curves C_P and C_Q are parameterized by $P(s)$ and $Q(s')$ respectively.

The problem is to determine for each point P on C_P a corresponding point Q on C_Q . For doing this, we must define a similarity measure which will compare locally the neighborhoods of P and Q .

As explained in the introduction, we assume that points of high curvature correspond to stable salient regions, and are therefore good landmarks to guide the matching of the curves. Moreover, we can assume as a first order approximation, that the curvature itself remains invariant in these regions. Therefore, we can introduce an energy measure in these regions of the form:

$$E_{curve} = \frac{1}{2} \int_{\delta S} (K_Q(s') - K_P(s))^2 ds \quad (1)$$

where K_P and K_Q denote the curvatures and s, s' parameterize the curves C_P and C_Q respectively. In fact, as shown by [7, 12], this is proportional to the energy of deformation of an isotropic elastic planar curve.

We also wish the displacement field to vary smoothly around the curve, in particular to insure a correspondence for points lying between two salient regions. Consequently we consider the following functional (similar to the one used by Hildreth to smooth a vector flow field along a contour [10]) :

$$E = \int_{C_P} (K_Q(s') - K_P(s))^2 ds + R \int_{C_P} \left\| \frac{\partial(Q(s') - P(s))}{\partial s} \right\|^2 ds \quad (2)$$

where

$$E_{regular} = \int_{C_P} \left\| \frac{\partial(Q(s') - P(s))}{\partial s} \right\|^2 ds$$

measures the variation of the displacement vector \vec{PQ} along the curve C_P , and the $\|.\|$ denotes the norm associated to the euclidean scalar product $\langle ., . \rangle$ in the space R^2 .

The regularization parameter $R(s)$ depends on the shape of the curve C_P . Typically, R is inversely proportional to the curvature at P , to give a larger weight to E_{curve} in salient regions and conversely to $E_{regular}$ to points inbetween. This is done continuously without annihilating totally the weight of any of these two energies (see section 5.2) .

3 Mathematical Formulation of the Problem

Given two curves C_P and C_Q parameterized by $s \in [0, 1]$ and $s' \in [0, \alpha]$ (where α is the length of the curve C_Q), we have to determine a function f such that:

$$f : [0, 1] \rightarrow [0, \alpha]$$

$$s \rightarrow s'$$

satisfying

$$f(0) = 0 \text{ and } f(1) = \alpha \quad (3)$$

and

$$f = \text{ArgMin}(E(f)) \quad (4)$$

where

$$E(f) = \int_{C_P} (K_Q(f(s)) - K_P(s))^2 ds + R \int_{C_P} \left\| \frac{\partial(Q(f(s)) - P(s))}{\partial s} \right\|^2 ds \quad (5)$$

The condition (3) means that the displacement vector is known for one point of the curve. In the trivial case, where the curves C_P and C_Q are identical, solving (4) leads to the identity function.

In the model defined above we assumed that:

- the boundaries have already been extracted,
- the curvatures K are known on the pair of contours.

These necessary data are obtained by preprocessing the image sequence.

3.1 Boundaries Extraction

The boundaries of the object are obtained with the deformable model [5]. This produces a good boundary extraction, the detected edges are connected and have an accurate localization. The deformable model allows also to do a global boundary tracking. This last feature is important in processing an image sequence, since in this case the deformable model has to be initialized only once on the first image of the temporal sequence.

3.2 The Computation of the Curvature

The computation of the curvatures of the two curves C_P and C_Q is done by fitting a fourth order B-spline (insuring a C^3 continuity) to the extracted boundaries. The control points of the B-spline are distributed in a non uniform manner, insuring a good localization of the control points near the points of interest (typically high curvature points). The details of this method are given in [8].

4 Numerical Solution

The characterization of a function f satisfying $f = \text{ArgMin}(E(f))$ and the condition (3) is performed by a variational method. This method characterizes a local minimum f of the functional $E(f)$ as the solution of the Euler-Lagrange equation $\nabla E(f) = 0$.

Then solving the Euler-Lagrange equation $\nabla E(f) = 0$ leads to the solution of the partial differential equation:

$$\begin{cases} f'' \|Q'(f)\|^2 + K_P \langle N_P, Q'(f) \rangle + \frac{1}{R} [K_P - K_Q(f)] K'_Q(f) = 0 \\ + \text{Boundary conditions} \end{cases} \quad (6)$$

where Q is a parametrization of the curve C_Q , $Q'(f)$ the tangent vector of C_Q , K'_Q the derivative of the curvature of the curve C_Q and N_P is the normal vector to the curve C_P . The boundary conditions of equation (6) are $f(0) = 0$ and $f(1) = \alpha$ (condition (3)) that any solution must satisfy. In the following we consider null boundary conditions (this is done by a simple change of variables).

The equation (6) is solved by a finite element method. Details on the associated variational problem and the construction of the approximation space can be found in the appendix.

The term $\int_{C_P} (K_Q(f(s)) - K_P(s))^2 ds$ measures the difference between the curvature of the two curves. This induces a non convexity of the functional E . Consequently, solving the partial differential equation (6) will give us a local minimum of E . To overcome this problem we will assume that we have an initial estimation f_0 which is a good approximation of the real solution (the definition of the initial estimation f_0 will be explained later). This initial estimation defines a starting point for the search of a local minimum of the functional E . To take into account this initial estimation we consider the associated evolution equation:

$$\begin{cases} \frac{\partial f(s)}{\partial t} + f''(s) \|Q'(f(s))\|^2 + K_P(s) \langle N_P(s), Q'(f(s)) \rangle + \frac{1}{R} [K_P(s) - K_Q(f(s))] K'_Q(f(s)) = 0 \\ f(0, s) = f_0(s) \text{ initial estimation.} \end{cases} \quad (7)$$

A stationary solution of the equation (7) is a solution of (6), since, at a stationary state, the term $\frac{\partial f}{\partial t}$ vanishes and the obtained solution satisfies the equation (6).

This evolution equation can also be seen as a gradient descent algorithm toward a minimum of the energy E .

4.1 Discrete Problem

The discretization of the equation (6) by a finite element method leads to a solution of a linear system $Af = L$, where the matrix A is symmetric, positive definite and tridiagonal. Thus the evolution problem (7) can be rewritten as:

$$\frac{\partial f}{\partial t} + Af = L_f \quad (8)$$

where the vector L_f depend on the current solution f . This equation is discretized by a finite difference method and leads to the solution of the linear system:

$$\begin{cases} (I_d + \tau A)f_t = f_{t-1} + \tau L_{f_{t-1}} \\ f_{t=0} = f_0 \end{cases} \quad (9)$$

where τ is the time step.

Thus at each time step we solve a symmetric, positive definite, tridiagonal linear system by a LU decomposition.

The scheme (9) is iterated as long as $\|f_t - f_{t-1}\|$ is greater than a given value $\epsilon > 0$.

4.2 Determining the Initial Estimation f_0

The definition of the initial estimation f_0 has an effect upon the convergence of the algorithm. Consequently a good estimation of the solution f will lead to a fast convergence. The definition of f_0 is based on the work of Duncan *et al* [7]. The method is as follows:

Let $s_i \in [0, 1]$, $i = 1 \dots n$ be a subdivision of the interval $[0, 1]$.

For every point $P_i = (X(s_i), Y(s_i))$ of the curve C_P we search for a point $Q_i = (X(s'_i), Y(s'_i))$ on the curve C_Q , and the function f_0 is then defined by $f_0(s_i) = s'_i$.

For doing so we have to define a pair of points P_0, Q_0 which correspond to each other. But, first of all, let us describe the search method. In the following, we identify a point and its curvilinear abscissa (*i.e.* the point s_i denotes the point P_i of the curve C_P such that $P(s_i) = P_i$, where P is the parametrization of the curve C_P).

For each point s_i of C_P we associate a set of candidates S_i on the curve C_Q . The set S_i defines the search area. This set is defined by the point s' which is the nearest distance point to s_i belonging to the curve C_Q , along with $\frac{N_{search}-1}{2}$ points of the curve C_Q on each side of s' (where N_{search} is a given integer defining the length of the search area).

The length of the search area plays an important role in the determination of f_0 . The parameter N_{search} depends on the shape of the curves C_P and C_Q . If the curve C_Q is similar to C_P (i.e. if C_P undergoes small deformations) then N_{search} can be small. But in the opposite case N_{search} must be large enough to include the corresponding points of C_P and C_Q . In the presented experimental results we have set $N_{search} = 10$.

Among these candidates, we choose the point which minimizes the deformation energy:

$$E = \frac{1}{2} \int_{\delta S_i} (K_Q(f(s)) - K_P(s))^2 ds \quad (10)$$

where $\delta S_i = [s_i - \frac{\delta}{2}, s_i + \frac{\delta}{2}]$ and δ denotes the length of a characteristic structure.

The length of the characteristic structure depends on the shape of the curve C_P . If the curve C_P has small structures (such that corners) the parameter δ must be small, not to smooth these structures by computing E (10) over a large set δS_i . This parameter allows to do a local matching process between the curves C_P and C_Q .

In some situations this method fails, and the obtained estimation f_0 is meaningless, leading to a bad solution. Figure 9 shows an example where the method described in [7] fails. This is due to the bad computation of the search area S_i . To compute more accurately this set, we have added a criterion based on the curvilinear abscissa. Consequently, the set defining the search area S_i is defined by the point s' which is the nearest distance point to s_i belonging to the curve C_Q such that $s'_i \approx \frac{s_i}{\alpha}$, along with $\frac{N_{search}-1}{2}$ points of the curve C_Q on each side of s'_i .

Figure 10 illustrates the use of this new definition of the set S_i for the same curves given in figure 9. This example shows the ability to handle more general situations with this new definition of the search area S_i .

As noted above, the search area S_i can be defined only if we have already chosen a point P_0 and its corresponding point Q_0 . The most salient features in a temporal sequence undergo small deformations at each time step, thus a good method for choosing the point P_0 is to take the most distinctive point so that the search for the corresponding point becomes a trivial task. Consequently the point P_0 is chosen among the points of C_P with maximal curvature. In many cases this method provides a unique point P_0 . Once we have chosen the point P_0 , the point Q_0 is found by the local

search described above.

5 Defining the Parameters

In this section we discuss the choice of the parameters used in our model. The parameters are: the space discretization step h , the time step τ and the regularization parameter $R = R_{C_P}(s)$.

5.1 The Space and Time Steps h and τ

We have shown that solving equation (7) leads to a solution of a linear system (9). This system is solved at each time step τ and the accuracy of the solution depends on the value of $Cond(I_d + \tau A) = \|I_d + \tau A\| \|(I_d + \tau A)^{-1}\|$ which is the condition number of the matrix $(I_d + \tau A)$. In the optimal case $Cond(I_d + \tau A) = 1$. In practice we will choose the parameters h and τ such that $Cond(I_d + \tau A)$ is closest to one. An easy way to do so is to search for an upper bound of $Cond(I_d + \tau A)$ and then choose the space and step discretization steps such that the upper bound is closest to one.

Let us consider the matrix norm:

$$|||(a_{ij})_{i,j=1\dots n}||| = \frac{1}{\sqrt{n}} \left(\sum_i \sup_j |a_{ij}|^2 \right)^{\frac{1}{2}}$$

thus,

$$Cond(I_d + \tau A) \leq 1 + \frac{n}{n+2} \left(\frac{\beta}{1+\beta} \right)^2$$

where n is the dimension of the matrix A and $\beta = \frac{6\tau}{5h}$ is the diagonal element of the matrix A (β is obtained by the finite element method).

Consequently, choosing $\beta \simeq 1$ which means that h and τ have similar values, leads to:

$$Cond(I_d + \tau A) < 1.12,$$

insuring that the matrix $I_d + \tau A$ is well-conditioned.

5.2 The Regularization Parameter $R = R_{C_P}(s)$

The energy E (5) is defined by an energy of deformation E_{curve} which measures the difference between the curvatures of C_P and C_Q and a regularization energy $E_{regular}$ which constrains the solution f to be smooth. The balance between these two energies is defined by the regularization parameter $R_{C_P}(s)$.

The parameter $R(C_P)$ allows the algorithm to deal with curves which have locally a constant curvature. In this case the energy E_{curve} is locally constant and the regularization parameter $R(C_P)$ constrains the solution to be smooth. In this case setting $R(C_P) = 0$ the energy E is locally constant and consequently any function $f \in H^1(0, 1)$ satisfies $\nabla E(f) = 0$, leading to a degenerate case.

Experimenting the algorithm with different types of curves gave us an empirical method for choosing the regularization parameter $R(C_P)$. If the curves C_P and C_Q have some characteristic points (typically points of high curvature), one then choose $R(C_P)$ such that the energy E_{curve} is preponderant. In the opposite case, *i.e* if the curvatures K_P and K_Q are nearly constant (in this case we have the situation described above), one must choose the parameter $R(C_P)$ such that the energy $E_{regular}$ is preponderant.

In both cases the parameter $R(C_P)$ should not have the extremal values $R(C_P) = 0$ or $R(C_P) \gg 1$. If $R(C_P) = 0$ then each point matches the point of closest curvature, leading to function f very rough. Setting $R(C_P) \gg 1$ leads to an excessive regularization and the obtained solution will be the identity function.

In the presented experimental results we set $R(C_P) = \frac{1}{1 + K_P(s)^2}$.

6 Experimental Results

The method was tested on a set of synthetic and real image sequences. The results are given by specifying at each discretization point P_i $i = 1 \dots N$ of the curve C_P the displacement vector $\vec{u}_i = P_i \vec{Q}_i$. At each point P_i the arrow represents the displacement vector \vec{u}_i .

The first experiments were made on synthetic data. In figure 3, the curve C_Q (a square) is obtained by a similarity transformation (translation, rotation and scaling) of the curve C_P (a rectangle). The initial estimation f_0 is shown in figure 3, and the solution after a few iterations of the scheme (9) is given in figure 4. We can note that the algorithm computes accurately the displacements of the four corners. This result was expected since the curves C_P and C_Q have salient features which help the algorithm to compute accurately the displacement vector \vec{u}_i .

Figure 5 and 6 give an example of the tracking of each point on an ellipse deformed by a similarity. This figure illustrates the robustness of the algorithm, since in this example, locally, the curvature is modified by the similarity transformation.

These two examples characterize the algorithm: the displacement vectors are computed accu-

rately when, locally, the curvature of the curve C_P varies significantly, otherwise the regularization energy prevails over the deformation energy and smoothes the solution.

As described in section (4.2) the computation of the initial estimation is crucial. In the following experimentation we have tried to define the maximal error that can be done on the estimation of f_0 without disturbing the final result. In figure 7 we have added a gaussian noise ($\sigma = 0.05$) to a solution f obtained by the scheme (9). This noisy function was taken as an initial estimation for the iterative scheme (9). After a few iterations the solution f is recovered (8). It appears that if $|f - f_0| \leq 4h$ (where h is the space discretization step), starting with f_0 the iterative scheme (9) will converge toward the solution f . The inequality $|f - f_0| \leq 4h$ means that for each point P on the curve C_P the corresponding point Q can be determined with an error of 4 points over the grid of the curve Q .

The tracking of the moving boundaries of the valve of the left ventricle on an ultrasound image helps to diagnose some heart diseases. The figures 12, 13, 14 and 15 show a temporal tracking of each point of the valve during a cardiac cycle. The segmentation of the moving boundaries over the whole sequence was done by the snake model [5]. Figure (2,left) shows the initial estimation of the boundary. This estimation is given by the user once on the first image of the temporal sequence, the rest of the sequence is processed almost automatically [9]. The user gave 4 initial estimations for the whole temporal sequence (30 images) due to the movements of the valve which undergoes big deformations at some characteristics periods of the cardiac cycle. Figure (2,right) shows the obtained segmentation of the boundary of the first image. In figure 11 a global tracking of a part of the image sequence is showed¹. This set of curves are processed as described in section (3.2) to obtain the curvatures and the normal vector of the curves. The figures 12, 13, 14 and 15 show the tracking of some points of the valve during the whole temporal sequence. The results are presented by pairs of successive contours. One can visualize that the results meet perfectly the objectives of preserving the matching of high curvature points while insuring a smooth displacement field.

7 3-D Generalization

In this section we give a 3-D generalization of the algorithm described in the previous sections. In 3-D imaging we must track points on located surfaces, since the objects boundaries are surfaces (as in [1]).

¹Courtesy of I. Herlin [9]

In [15] the authors have shown on a set of experimental data, that the extrema of the larger principal curvature often correspond to significant intrinsic (i.e. invariant by the group of rigid transformation) features which might characterize the surface structure, even in the presence of small anatomic deformations.

Let S_P and S_Q be two surfaces parameterized by $P(s, r)$ and $Q(s', r')$, and let κ_P denote the larger value of the principal curvature of the surface S_P at point P .

Thus the matching of two surfaces, leads to the following problem:

find a function

$$\begin{aligned} f: R^2 &\rightarrow R^2 \\ (s, r) &\mapsto (s', r') \end{aligned}$$

which minimizes the functional:

$$\begin{aligned} E(f) = & \int_{S_P} (\kappa_Q(f(s, r)) - \kappa_P(s, r))^2 ds dr \\ & + R_s \int_{S_P} \left\| \frac{\partial(Q(f(s, r)) - P(s, r))}{\partial s} \right\|^2 ds dr + R_r \int_{S_P} \left\| \frac{\partial(Q(f(s, r)) - P(s, r))}{\partial r} \right\|^2 ds dr \end{aligned}$$

where $\|\cdot\|$ denotes the euclidean norm in R^3 . Its resolution by a finite element technique can be done as in [4], and the results should be compared to those obtained by [1]. We are currently working on the implementation of this 3-D method.

8 Conclusion

We presented a significant improvement to Duncan's team approach to track the motion of deformable 2-D shapes, based on the tracking of high curvature points while preserving the smoothness of the displacement field. This approach is an alternative to the other approaches of the literature, when no physical or geometric model is available, and can also be used as a complementary approach otherwise.

The results on a real sequence of time varying anatomical structure of the beating heart perfectly meet the defined objectives.

Our future work will concentrate on the 3-D generalization of this approach.

9 Appendices

In this section we give the details about the minimization of the energy (5). This minimization is done in three stages. First, establish the partial differential equation from the Euler-Lagrange equation. Second, construct the associated variational problem and then solve this problem with a finite element method [3].

9.1 Euler-Lagrange Equation

A local minimum of E (5) satisfies the Euler-Lagrange equation: $\nabla E = \nabla E_{curve} + R\nabla E_{regular} = 0$

For any function u , we have:

$$\nabla E_{curve}(f) \cdot u = -2 \int_{C_P} [K_P(s) - K_Q(f(s))] K'_Q(f(s)) u ds \quad (11)$$

and

$$\begin{aligned} \nabla E_{regular}(f) \cdot u &= -2 \int_{C_P} \left\langle \frac{\partial(P(s) - Q(f(s)))}{\partial s}, \frac{\partial}{\partial s} (Q'(f(s))u(s)) \right\rangle ds \\ &= -2 \int_{C_P} \left\langle \frac{\partial^2(Q(f(s)) - P(s))}{\partial s^2}, Q'(f(s))u(s) \right\rangle ds \\ &= -2 \int_{C_P} \langle f''(s)Q'(f(s)) + f'(s)Q''(f(s)) - P''(s), Q'(f(s)) \rangle u(s) ds \end{aligned}$$

Q is a parametrization of the curve C_Q thus $\langle Q', Q'' \rangle = 0$ (where the $\langle \cdot, \cdot \rangle$ denotes the euclidean scalar product in R^2 and $\|\cdot\|$ the associated norm). We have also the relation

$$P''(s) = -K_P(s)N_P(s)$$

where P'' denotes the second derivatives of P , K_P the curvature and N_P the normal vector to the curve C_P . Hence,

$$\nabla E_{regular}(f) \cdot u = -2 \int_{C_P} \left(f''(s) \|Q'(f(s))\|^2 + K_P(s) \langle N_P(s), Q'(f(s)) \rangle \right) u(s) ds \quad (12)$$

Since the equations (11,12) are satisfied, independently of the function u , we have the partial differential equation:

$$\begin{cases} f'' \|Q'(f)\|^2 + K_P \langle N_P, Q'(f) \rangle + \frac{1}{R} [K_P - K_Q(f)] K'_Q(f) = 0 \\ + \text{Boundary conditions} \end{cases} \quad (13)$$

given in section 4.

9.2 The Variational Problem

A method for solving the equation (13) is to consider the associate variational problem. This consists in defining a bilinear form $a(f, g)$ and a linear form L such that solving the equation (13) is equivalent to solve:

find a function f such that:

$$a(f, g) = L(g) \quad \forall g \in H^1(0, 1) \quad (14)$$

($H^1(0, 1)$ is the space of functions $v \in L^2(0, 1)$ such that $\int_0^1 \left(\frac{dv}{ds}\right)^2 ds < +\infty$).

Let $g \in H^1(0, 1)$, multiplying equation (13) by g and integrating it, yields:

$$\int_0^1 \|Q'(f)\|^2 f' g' ds = \int_0^1 \left(K_P \langle N_P, Q'(f) \rangle + \frac{1}{R} [K_P - K_Q(f)] K_Q'(f) \right) g ds$$

The bilinear form is then defined by:

$$a(f, g) = \int_0^1 \|Q'(f)\|^2 f' g' ds$$

and the linear form L is given by:

$$L(g) = \int_0^1 \left(K_P \langle N_P, Q'(f) \rangle + \frac{1}{R} [K_P - K_Q(f)] K_Q'(f) \right) g ds$$

One can easily check that f is a solution of equation (13) if and only if f is a solution of the variational problem (14).

The variational problem (14) has a unique solution since the bilinear form $a(f, g)$ is continuous, H^1 -elliptic and L is continuous.

9.3 Obtaining the Discrete Problem: The Finite Element Method

So far, we have been dealing with the continuous form of the equation (13) to show the existence and the uniqueness of the solution. Here, we will use the Galerkin's method to approximate the variational problem (14) by a discrete problem defined over a finite dimensional subspace $V_h \subset H^1(0, 1)$. The associated discrete problem is:

$$\text{Find } f_h \in V_h \text{ such that } a(f_h, g_h) = L(g_h) \quad \forall g_h \in V_h. \quad (15)$$

To insure the convergence of f_h toward f (solution of 14), we construct the space V_h with the finite element method.

Let consider a subdivision $\bigcup_{i=1}^N [ih, (i+1)h]$ of the set $[0, 1]$ and a basis function $\{\phi_i\}_{i=1\dots N}$ of the subspace V_h (see figure 1). The space V_h , generated by these basis functions, fulfil the necessary conditions of the finite element method.

Thus $\forall f_h \in V_h$ we have $f_h = \sum_{i=1}^N f_h(ih) \phi_i$.

Using this relation the discrete problem (15) can be reformulated as:

$$\text{Find } f_h(ih), i = 1 \dots N \text{ such that } \sum_{i=1}^N f_h(ih) a(\phi_i, g_h) = L(g_h) \quad \forall g_h \in V_h \quad (16)$$

This equation (16) holds also for the basis functions $\{\phi_i\}_{i=1\dots N}$, hence the discrete variational problem can be rewritten as

$$\text{Find } f_h(ih), i = 1 \dots N \text{ such that } \sum_{i=1}^N f_h(ih) a(\phi_i, \phi_j) = L(\phi_j) \quad \forall j = 1 \dots N. \quad (17)$$

This gives a linear system $A \cdot F = L$ to solve, where $A = (a(\phi_i, \phi_j))_{i,j=1\dots N}$, $F = (f_h(ih))_{i=1\dots N}$ and $L = (L(\phi_i))_{i=1\dots N}$. The solution of the linear system $A \cdot F = L$ is done by a LU decomposition since the matrix A is positive definite, symmetric and tridiagonal.

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10 Figures

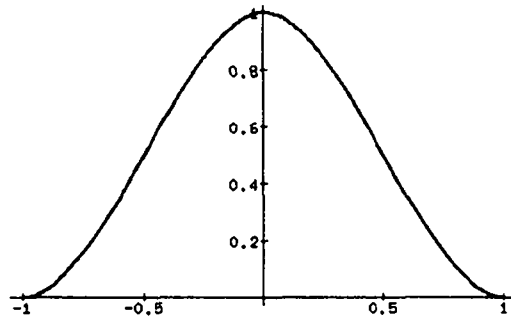


Figure 1: The finite element basis function used to discretize the continuous variational problem.

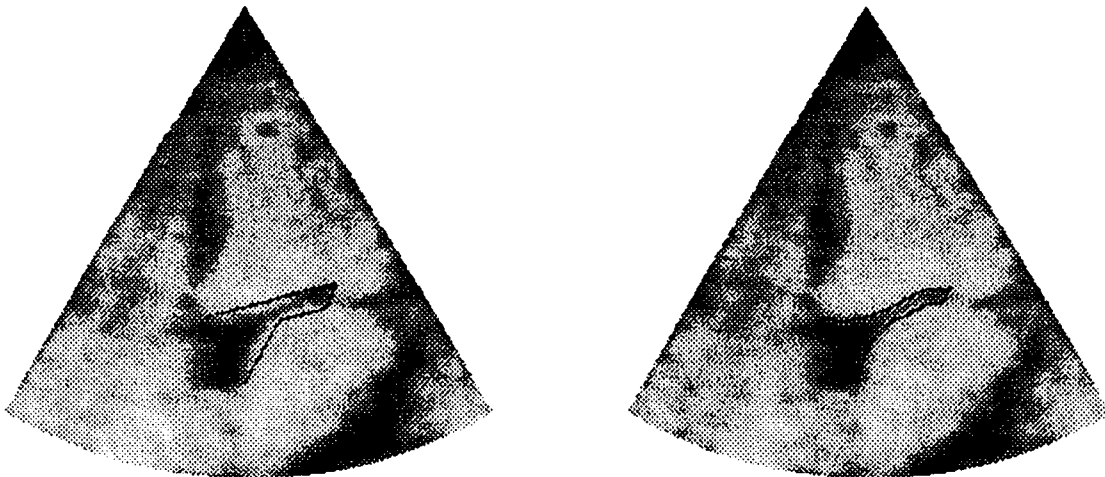


Figure 2: A example of processing the image sequence by a snake model to extract the boundaries of the moving object. Left: the initial estimation given by the user. Right: the boundary of the valve once the snake model have converged. The initial estimation is given only 4 times for a temporal sequence containing 30 images.

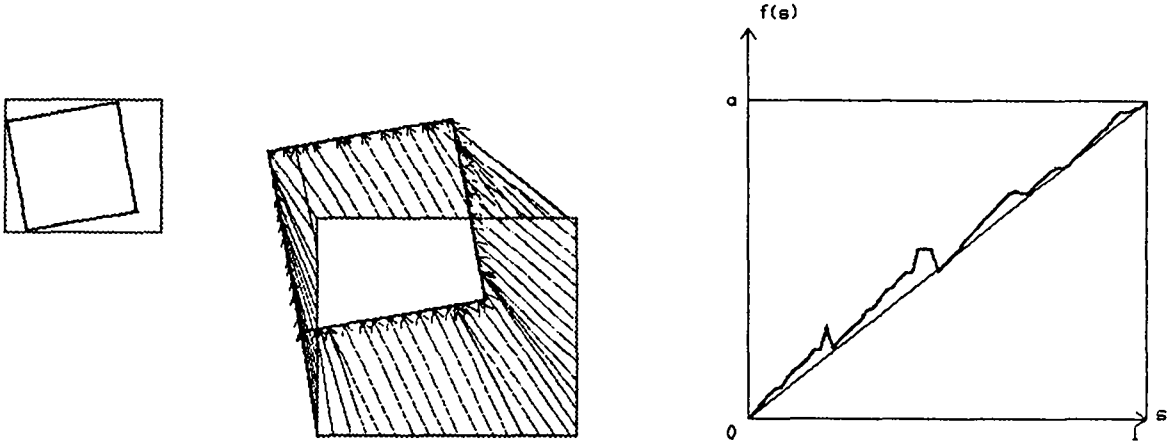


Figure 3: The rectangle (in grey) is deformed by a similarity (translation, rotation and scaling) to obtain the black square. In this figure we represent the initial estimation of the displacement vector of the curves (left) and the plotting of the function f_0 (right).

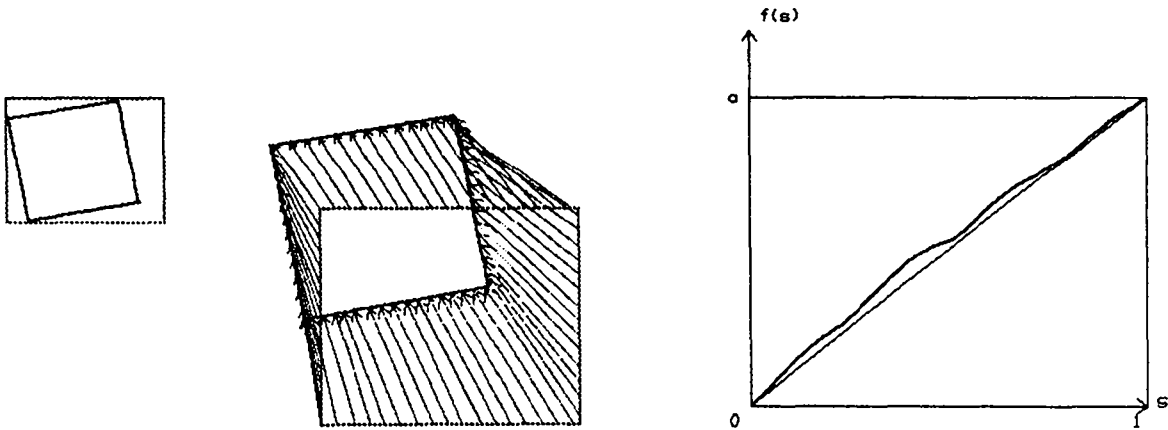


Figure 4: A representation (displacement field and the plotting) of the solution obtained by the algorithm. We can note that the displacement of the four corners is computed accurately.

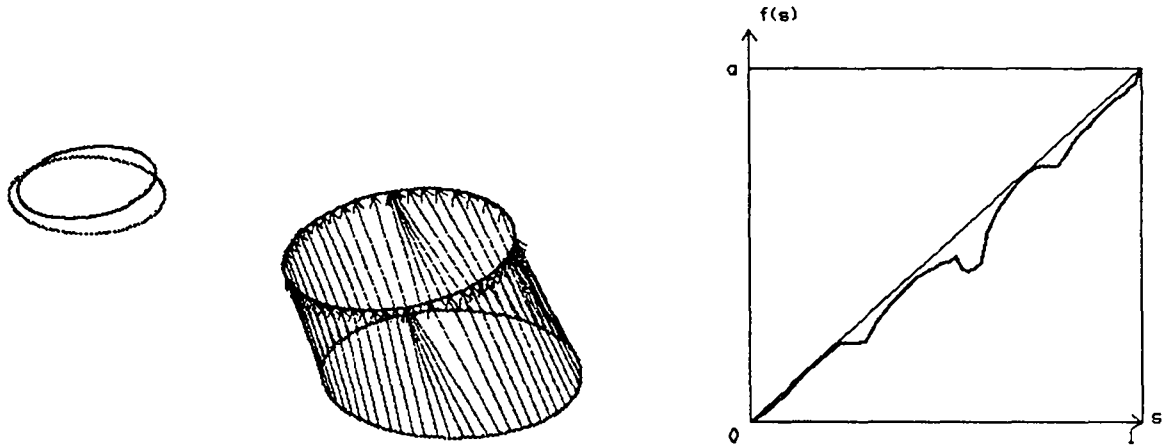


Figure 5: Another synthetic example, in this case the curvature along the curves C_P and C_Q varies smoothly. This often produces as a consequence in the computation of f_0 that several points of the curve C_P (in grey) match the same point of C_Q (in black).

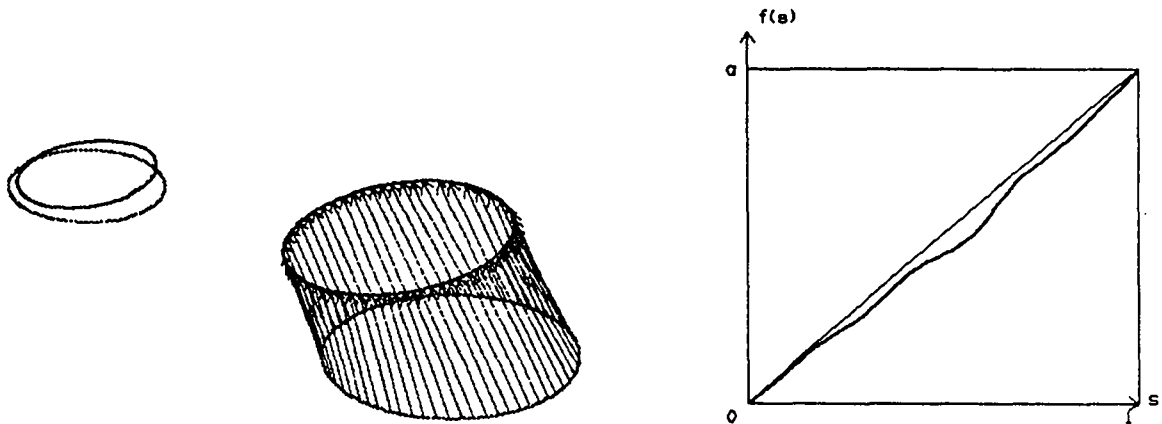


Figure 6: The optimal solution obtained by the algorithm. We remark that the each point of the black curve matches a single point of the grey curve, and that, maximum curvature points matched together.

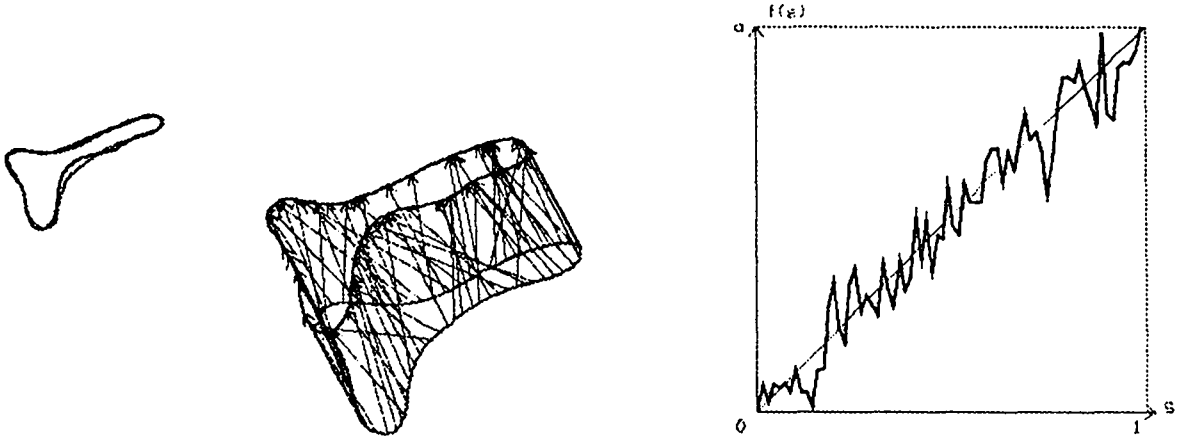


Figure 7: In this example we have corrupted an obtained solution with a gaussian noise ($\sigma = 0.05$) and considered this corrupted solution as an initial estimate f_0 .

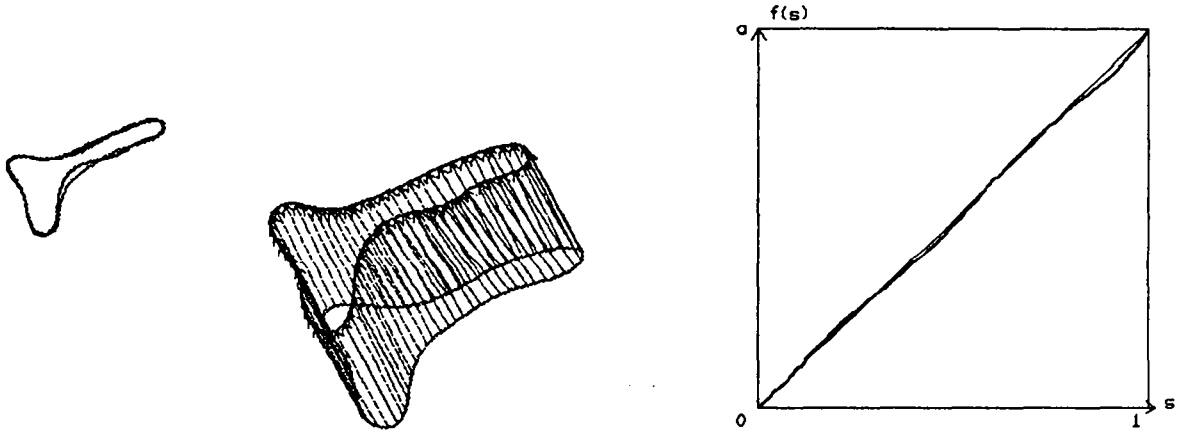


Figure 8: The minimum of E starting with the initial estimation plotted in the previous figure. We have noted that if $\|f - f_0\| < 4h$ the algorithm still converges towards the realistic solution.

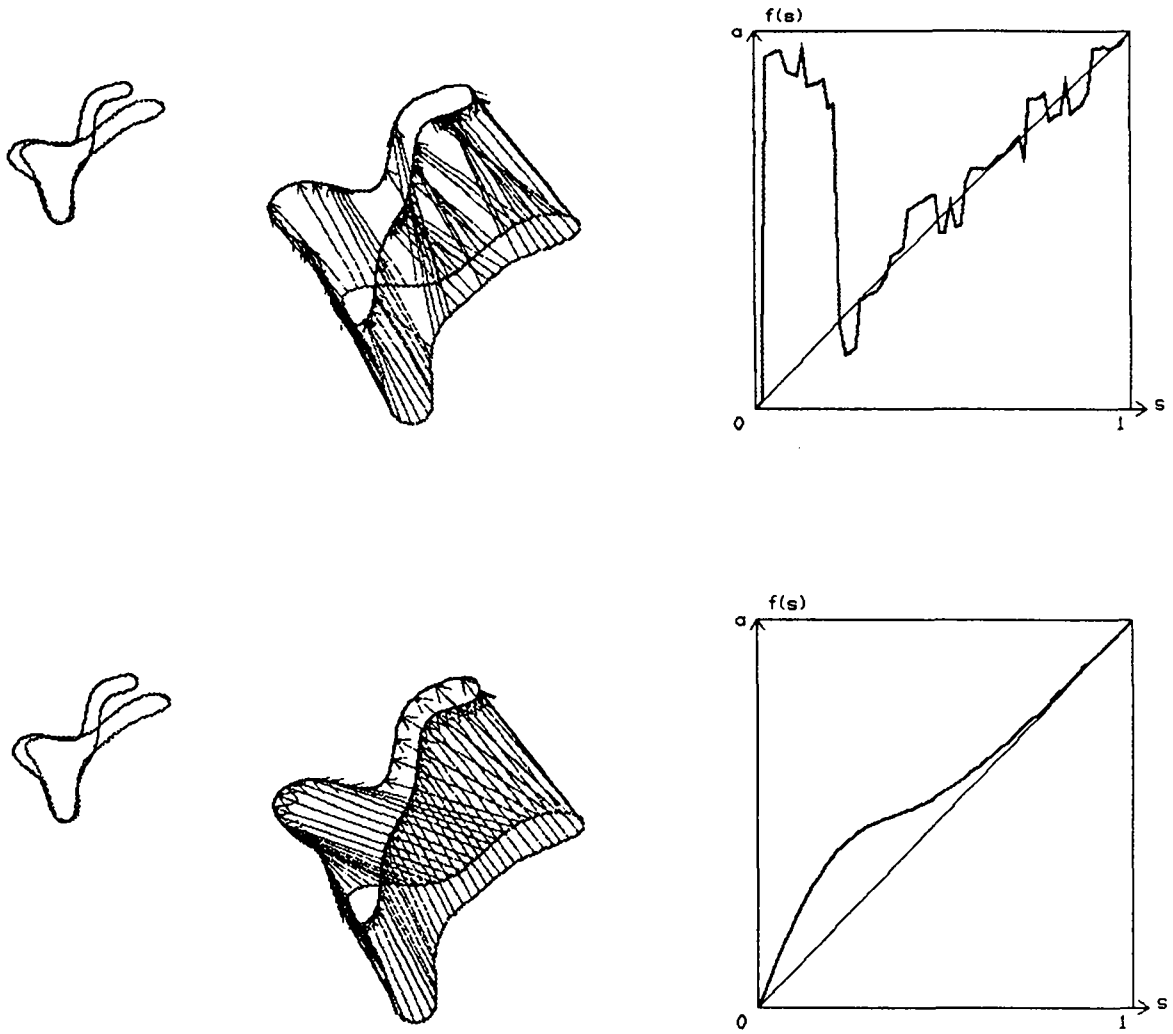


Figure 9: This example shows the problem that can occur in the computation of the initial estimate based only on the search in a given area. The initial estimation f_0 (top) and the obtained solution (bottom).

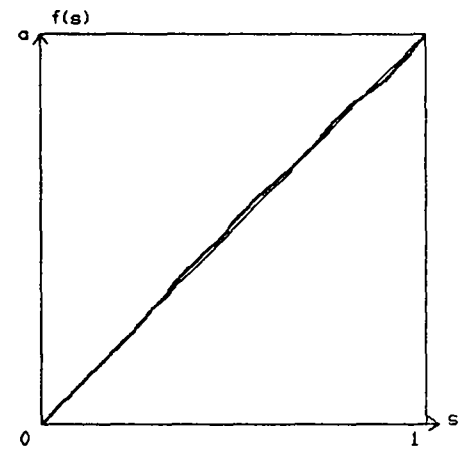
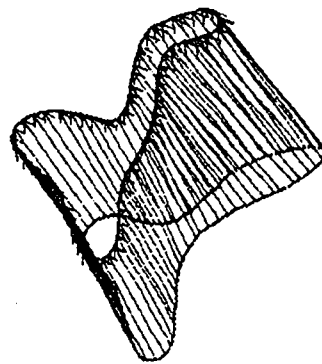
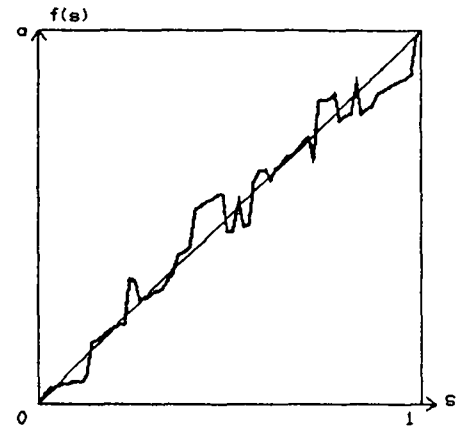
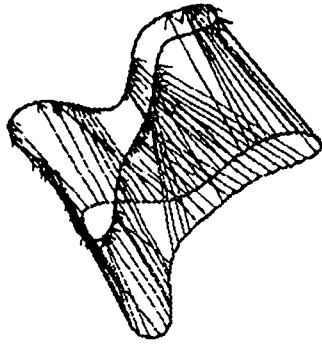


Figure 10: In the same case of the previous example, the computation of the initial estimate based on the local search and the curvilinear abscissa, gives a good estimation f_0 , which leads to an accurate computation of the displacement function.

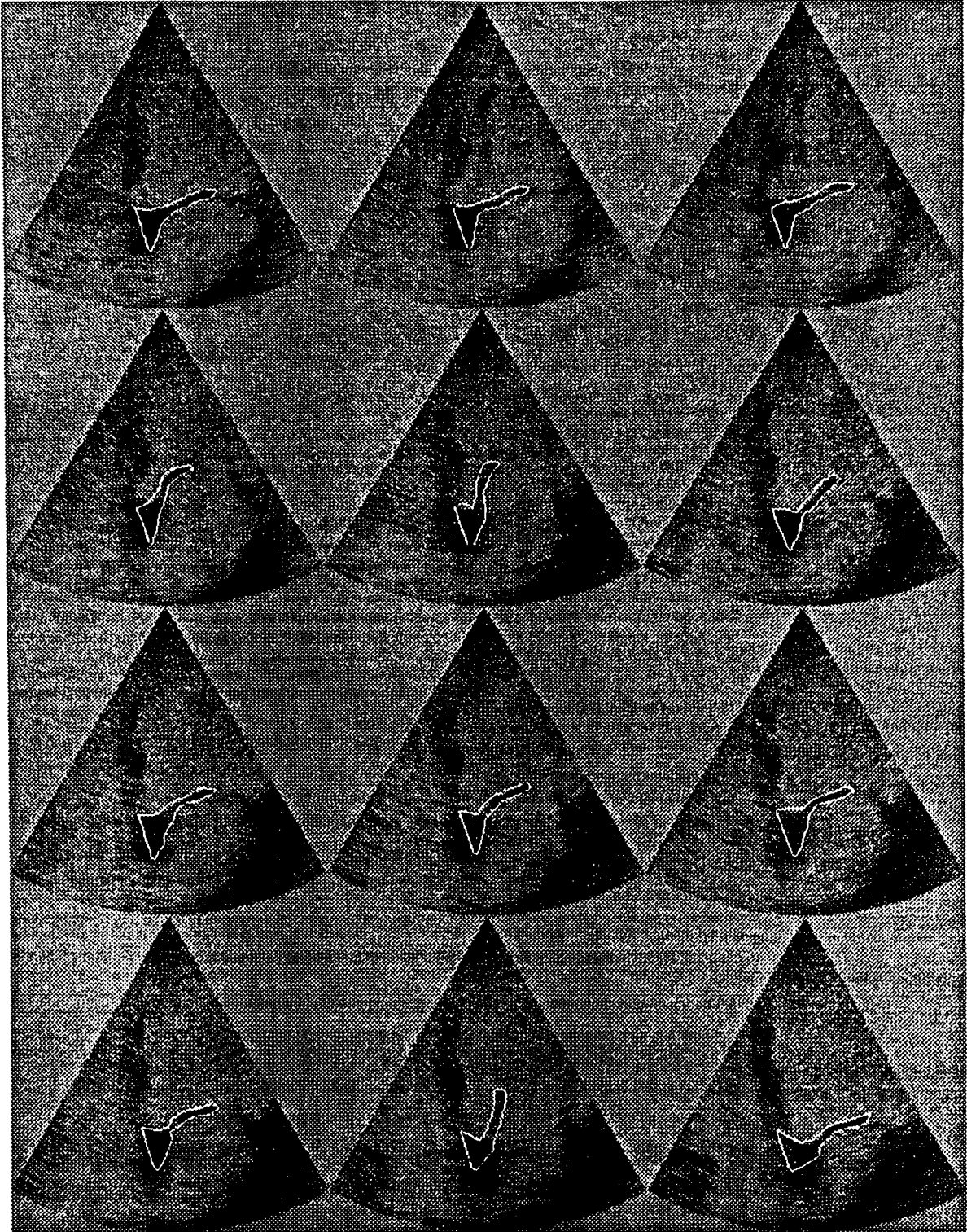


Figure 11: Temporal tracking of the mitral valve, obtained by the snake model[9].

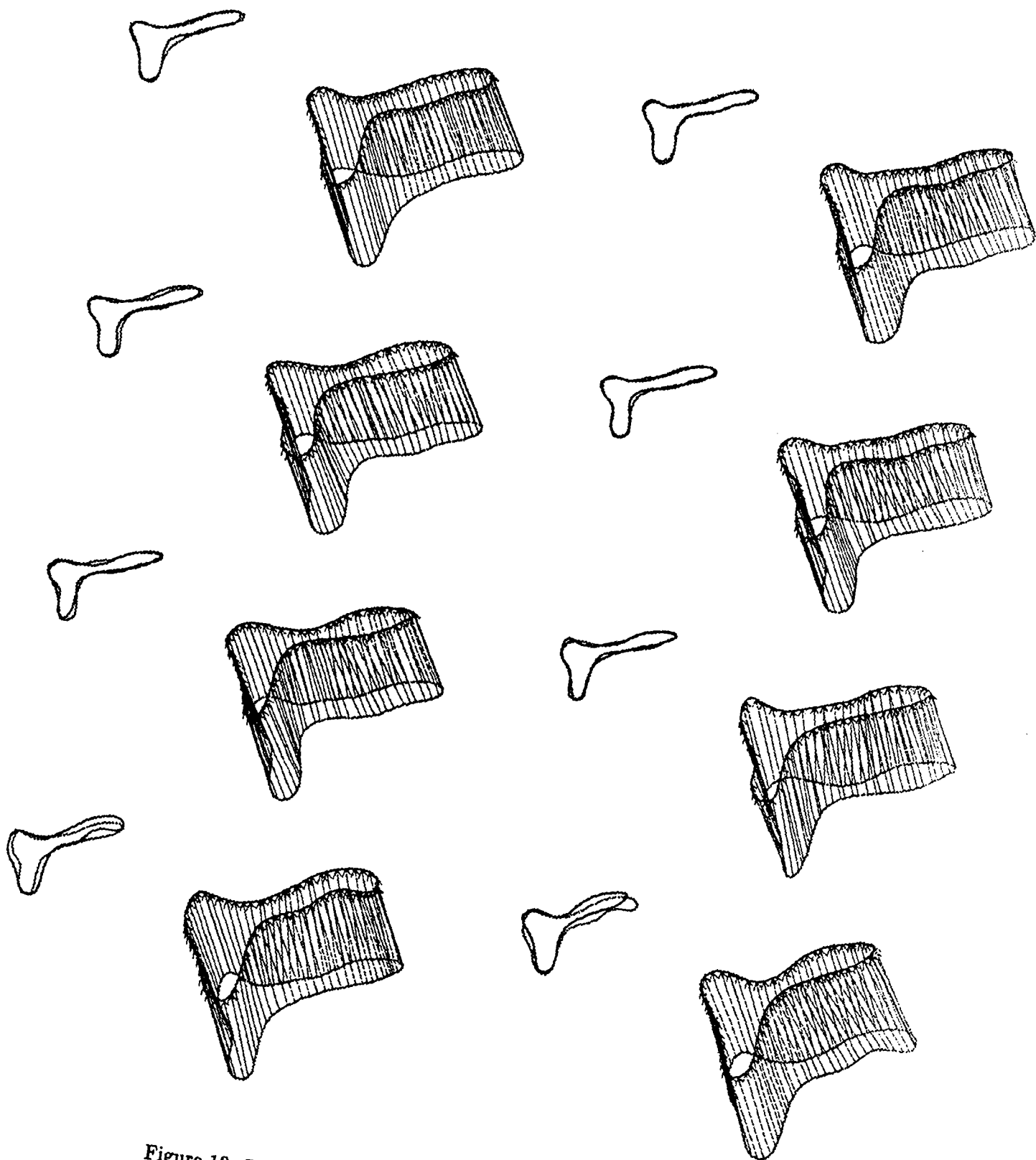


Figure 12: Experiments on a valve sequence (time 1-9).

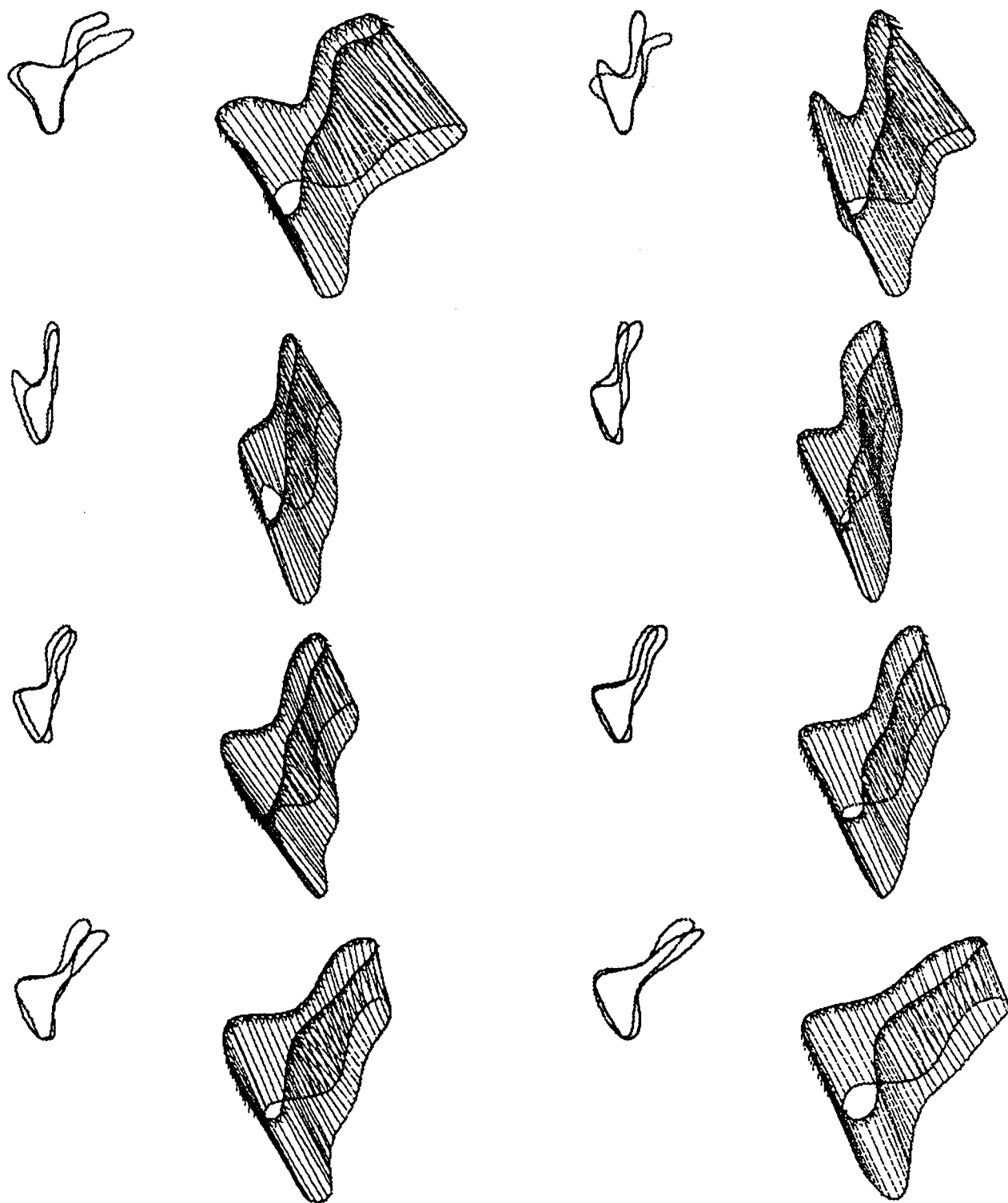


Figure 13: Experiments on a valve sequence (time 9-17)

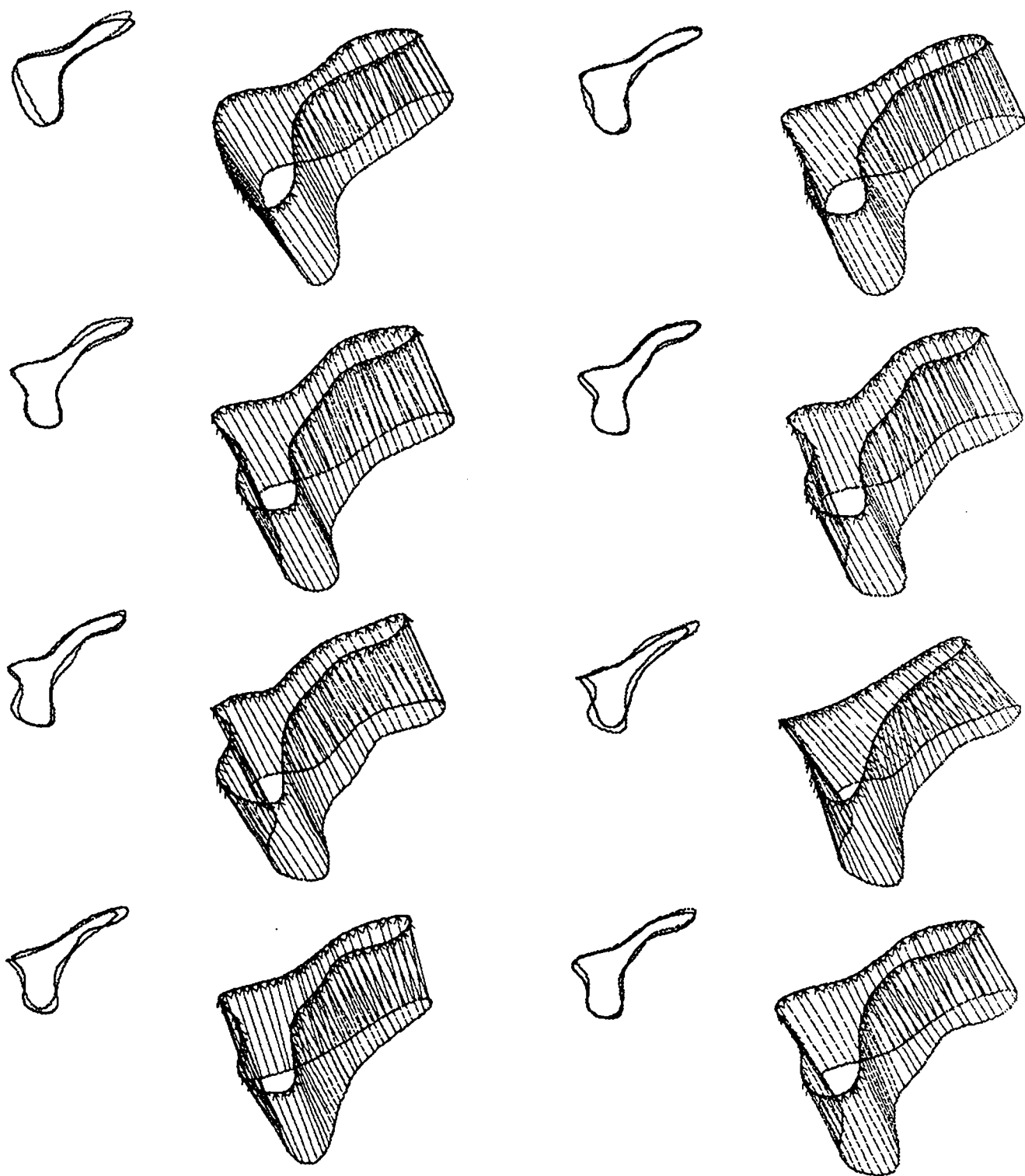


Figure 14: Experiments on a valve sequence (time 17-25)

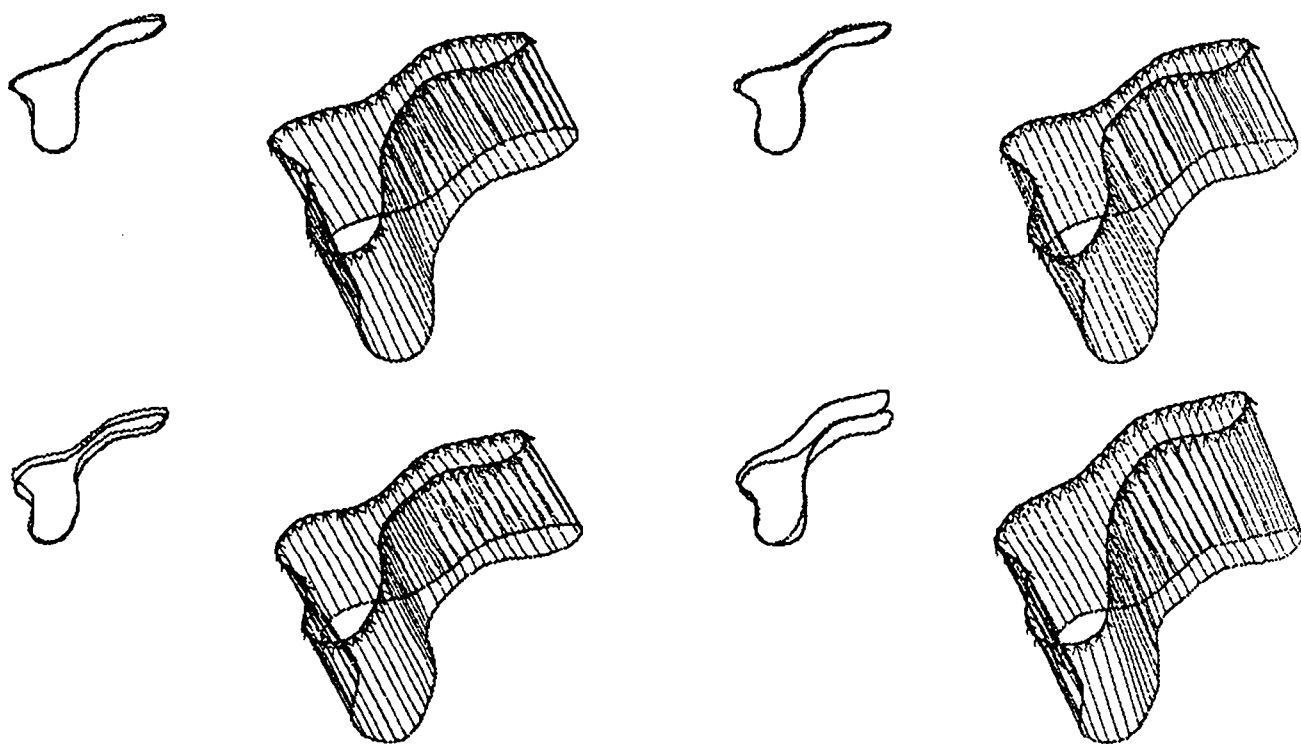


Figure 15: Experiments on a valve sequence (time 25-29)

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